DETECTION OF AIRCRAFT COMPONENT DEFECTS USING LOW VOLTAGE EXCITATION OF ULTRASONIC TRANSDUCERS

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INTRODUCTION

Large areas of composite primary structure are now to be found both on civil and military aircraft throughout the world and the inspection of these structures contributes significantly to overall operating costs. Therefore methods to reduce the inspection time, whilst maintaining an acceptable minimum defect detection capability, are required in order to optimize the potential cost saving benefits offered by using that carbon fiber composite material.

Composite structures are regularly inspected using ultrasonic techniques and various computer-based ultrasonic data acquisition systems have been developed to enhance the process [1]. Essentially the inspection process involves propagating high-intensity ultrasonic waves, generated by a piezoelectric transducer via an excitation pulse of several hundred volts amplitude, through the component under test, and examining the returned echoes. Ultrasonic linear array B-scan systems which were originally developed for medical applications have been adapted to meet the aerospace industry requirement and operation of this technology is now well established. However whilst increasing the structure area covered in a single pass of the transducer further expansion of this equipment to inspect larger two-dimensional areas would substantially increase hardware complexity and size, therefore reducing portability. For example, to inspect 100 square mm of carbon fiber composite with 1 mm resolution, 10000 separate pulser circuits would be required.

In this paper low voltage excitation of ultrasonic transducers is proposed as a practical solution to solve portability problems associated with the development of two-dimensional ultrasonic arrays for the aerospace industry. Results obtained from computer simulations and experiments are presented to demonstrate the feasibility of the proposal.

HIGH VOLTAGE EXCITATION METHODS

Generally, the excitation of ultrasonic transducers is accomplished using metal oxide semiconductor field effect transistors (MOSFETS) configured as switching devices. These devices are normally supplied with a high voltage, typically between 150 and 400 volts which short circuit the supply voltage to ground as the device is turned on and subsequently return to high voltage as the device is turned off, thus producing a single spike. For a typical transducer and associated electronic circuit combination the force produced at the transducer face is directly related to the excitation voltage, therefore using high voltage excitation has the distinct advantage of increasing sensitivity. However, problems do exist with high voltage devices in that they are non linear switching devices, and care has to be taken at the design stage in order to achieve the desired pulse shape for varying loads and different transducer frequencies.

Ideally a flexible transducer would allow larger areas to be inspected without component geometry affecting coupling. The use of polyvinylidene diflouride (PVDF) as the piezoelectric material offers the potential of manufacturing such a flexible transducer. However, using PVDF poses the problem that cable capacitances can significantly reduce the overall transducer sensitivity. To overcome this difficulty the pulser / receiver circuitry is normally positioned in the transducer housing close to the PVDF material, but as the number of elements increase, incorporating high voltage pulser/ receiver circuitry for each element in the housing is impractical. This is due to a single high voltage MOSFET typically occupying an area of 10 mm x 6 mm. Other disadvantages are that the resulting excessive component interconnections can lead to reduced system reliability, maintenance problems and difficulties in achieving reproducible performance. Also this excitation method requires a high voltage for the excitation circuit, ±5V to supply the digital control circuit and perhaps ± 15V for the amplification stages. This is generally accomplished by stepping up the voltage from a 12V battery using high frequency transformers and oscillator circuits, and if not properly filtered, the signal to noise ratio for the transducer circuitry may be significantly reduced.

LOW VOLTAGE EXCITATION

By reducing the amplitude of the excitation voltage from hundreds to tens of volts, the size of the electronic components required for the ultrasonic transducer excitation circuit can be significantly reduced and therefore the electronics required for the transducer excitation and subsequent data acquisition can be implemented using Very Large Scale Integration (VSLI) technology. This would result in small integrated circuits controlling all the system functions, thus the problems of over complex hardware and poor system portability can be alleviated. Furthermore, application specific integrated circuit (ASIC) technology can be used to reduce design time and prototype costs.

A reduction in the excitation voltage amplitude from 200 to 20 volts corresponds to a 20 dB reduction in sensitivity. However because low voltage MOSFETS behave linearly when operated as switching devices, and can be constructed to be tolerant to load variations more readily than high voltage devices the desired excitation pulse shape can be readily achieved, and therefore some of the loss in sensitivity can be restored.

Operation of a two-dimensional array is expected to be a *pick and place* sequence, with no transducer movement as the ultrasonic data is captured and displayed. This will allow more time for signal processing, to enhance the received signals. Also by having complete control over the design of the amplification stages improvements in the signal-to-noise ratio and gain are possible. In the next section of this paper, the results obtained by computer simulation are presented to demonstrate the feasibility of utilizing low voltage excitation for generating ultrasound through carbon fiber composite structures.

COMPUTER SIMULATION AND RESULTS

Pspice, a software package for circuit simulation studies was used to simulate the low voltage excitation of ultrasonic transducers. Figure 1 shows the simulation model consisting of two transducer sub-circuits connected together via a transmission line. In Figure 1, Vpulse represents the excitation voltage and Vout represents the received signal voltage, Cin and Rin represent the output impedance of the transducer driving circuit, and Rback represents the impedance of the transducer backing material.

The transducer sub-circuit shown if Figure 1 was modeled using an electronic equivalent circuit developed by Morris and Hutchens [2]. The four transducer sub-circuit ports shown in Figures 1 and 2 correspond to the numbers 1, 2, 3, and 4 in both figures. As shown in Figure 2, the transducer sub-circuit consists of an input resistor/capacitor network, a negative capacitance, an ideal transformer, and a transmission line.

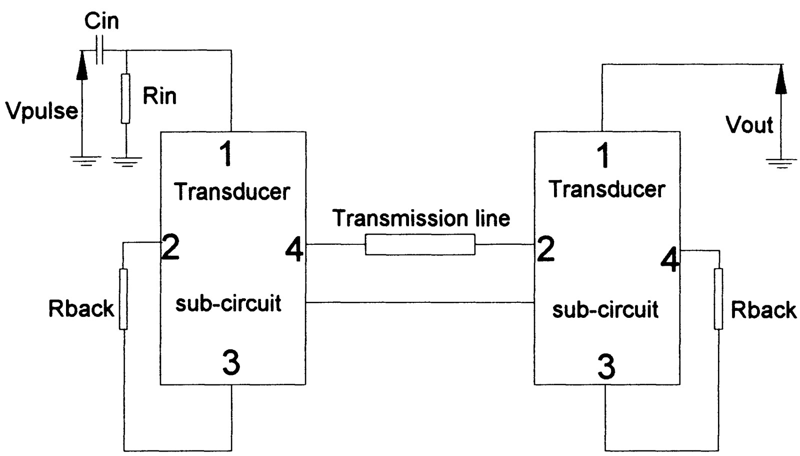


Figure 1 Through Transmission Pspice Simulation Circuit.

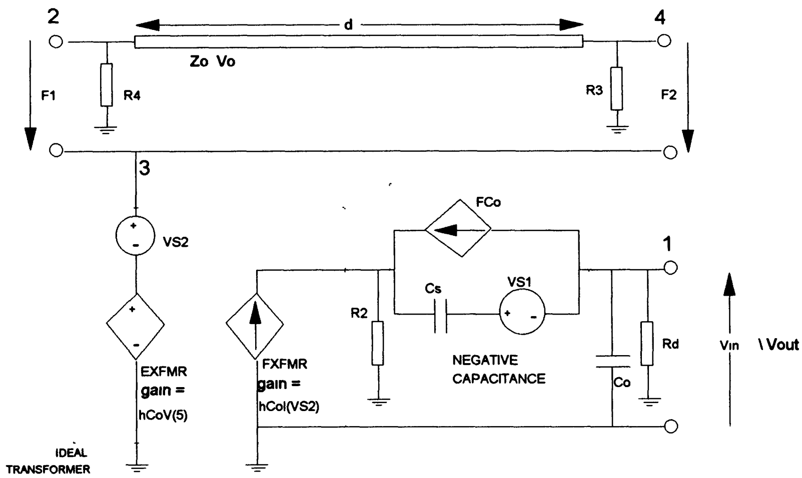


Figure 2 Equivalent transducer sub-circuit.

The input resistor/capacitance (Rd and Co) represents the dielectric losses and the static capacitance, respectively. For ceramic transducers the dielectric loss is negligible and is usually ignored however, using PVDF this dielectric loss is significant and therefore has to be taken into consideration. The negative capacitance [3] is simulated by a capacitor, Cs, in series with a independent voltage source, Vs, which are both in parallel with a current controlled current source, FCo (Figure 2). Positive current flows from the positive node of the FCo through Vs to the negative node of the FCo. The effect of this is to produce a charging current on the positive side of capacitor Cs, and hence produces an approximation of a negative capacitance. The ideal transformer simulates the electromechanical coupling of the transducer and utilizes a voltage controlled voltage source, EXFMR, and a current controlled current source, FXFMR coupled to an independent voltage source VS2. The conversion ratio of electrical energy to mechanical energy within a piezoelectric material is then calculated by equations (1) and (2) :

$$C_0 = (\varepsilon^s A) / (\tau\, v_0) \tag{1}$$

$$hC_0 = e_{33}\ C_0 / \varepsilon^s \tag{2}$$

where A is the transducer area, τ is the acoustic transit time, v_o is the velocity of sound, e_{33} is the dielectric constant of the material at constant strain, and ε^s is related to the relative dielectric constant ε_r by equation (3)

$$\varepsilon_r = \varepsilon^s / \varepsilon_o \tag{3}$$

The output of the ideal transformer is connected to the transmission line which contains inductance in both conductors. The transmission line stage represents the reverberations of ultrasound that occur in a piezoelectric material. The transmission line parameters are calculated using equations (4) and (5):

$$Z_0 = \rho\, v_0\, A \tag{4}$$

$$\tau = d / v_O \tag{5}$$

where Z_0 is the characteristic transmission line impedance, ρ is the material density and d is the material thickness

The amount transmitted into backing materials and the material under test is then dependent on the different values of acoustic impedance of each material.

The transducer parameters used in simulation study were (a)those derived by Berlincourt *et al* [4] in the case of PZT-5A material and (b) those obtained from AMP data sheets in the case of PVDF [5]. The material parameters values are tabulated in Table 1.

Modeling with the PVDF parameters showed that the desired performance was achieved when the transducer input capacitance was set to 500 pF, and a wide bandwidth was achieved when the value of the back load matched the impedance of the transmission line used in the transducer model i.e. an exact match between transducer impedance and back load impedance hence lossless transmission. Figure 3 shows the results of the PVDF transducer response produced by a 30 volt negative going square wave acting as the excitation pulse. By experimenting with the excitation pulse shape and duration, it was found that the best transducer response was achieved when the pulse rise and fall times were approximately 10ns or less, namely the timing of the pulse edges correspond to the natural expansion and contraction actions of the transducer material.

Table 1 Transducer parameters.

	PZT-5A	PVDF
Thickness d	0.435 mm	100 μm
Diameter	20mm	20 mm
Density ρ	7.75E3 kg/m^3	1.78E3 kg/m^3
Relative dielectric constant $\varepsilon^s/\varepsilon_o$	830	12
Velocity v_O	4350 m/s	2200 m/s

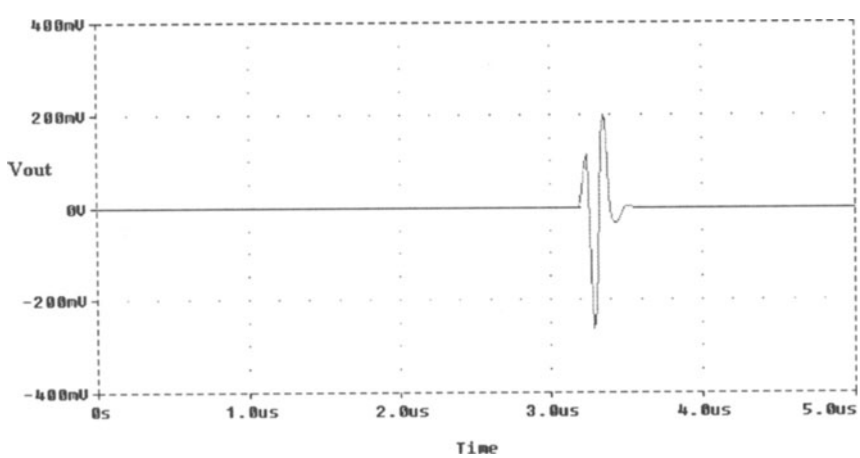


Figure 3 Pspice Simulation Result for PVDF Model, 30 Volt Excitation.

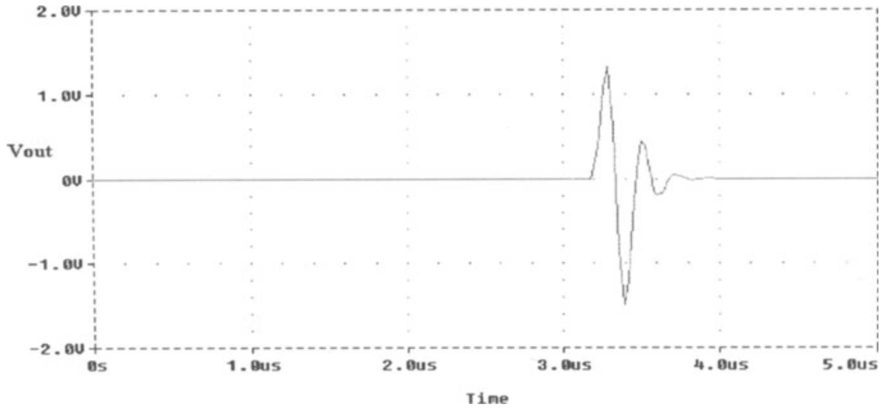


Figure 4 Pspice Simulation Result for PZT-5A, 30 Volt Excitation.

Modeling with the PZT parameters showed that best performance was achieved when the transducer input capacitance was 2mF. As with the PVDF case, wide bandwidth transducer response was achieved when the back load impedance matched the transducer characteristic impedance and the excitation pulse coincided with the natural transducer reverberations. Figure 4 shows the simulation results of the PZT transducer response produced using a 30 volt negative going square wave as the excitation pulse. experimentally.

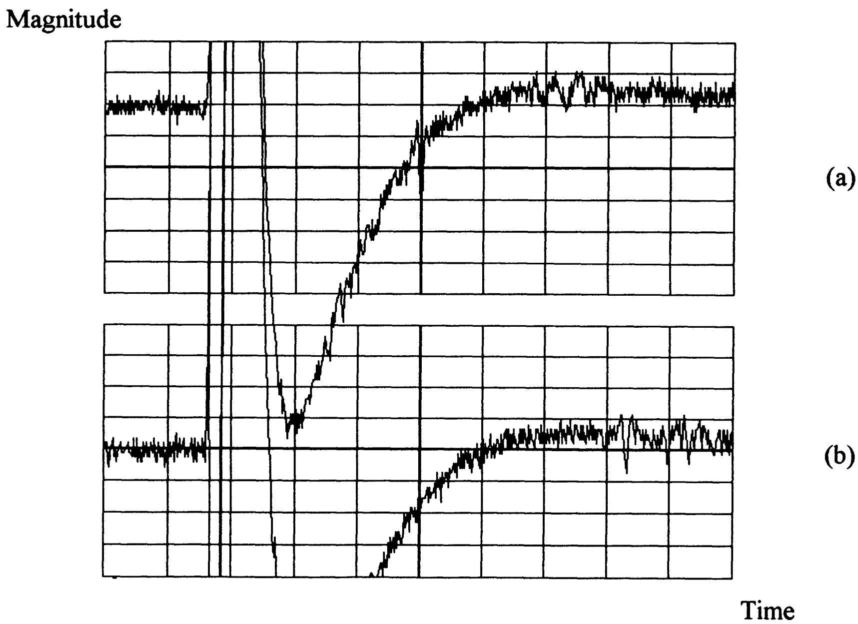
EXPERIMENTAL TESTS AND RESULTS

In order to confirm the feasibility of reducing the excitation voltage amplitude for ultrasonic inspection of carbon fiber composite material, experiments were carried out using a commercially available ultrasonic system, a standard 5 MHz PZT transducer and a PVDF, sheet 110 μm thick. An ultrasonic excitation pulse of ± 15V, and an amplification factor of 5 dB were used, for the experiment.

As previously calculated by Silk [6] the received signals from the commercially available PZT transducer were significantly larger in amplitude than the PVDF signals when transmitted through the same thickness of material. This is due to PVDF having a relatively low electromechanical coupling factor, which resulted in a transmit / receive efficiency five times less than that of PZT-5A. Another factor to consider is that the pulser/receiver was designed for high voltage ceramic transducer excitation /amplification which when used with PVDF material, reduces sensitivity. The signals displayed in Figure 5 show the backwall echos from 5 and 10 mm of carbon fiber composite material, and the signal amplitude is approximately 200 and 100 mV respectively. Figure 6 shows the corresponding signals obtained from PVDF material. The signal amplitude is significantly reduced in comparison with the PZT result, with the backwall amplitude being approximately 40 mV and 20 mV respectively for the 5 and 10mm material thickness. In comparison with the computer simulation results, the actual signal amplitude is significantly less, and is due to the attenuation of ultrasound in carbon fiber composite, which had not been included in the computer simulation model. Nevertheless, it can be clearly seen from the computer simulation results and the experimental results, that the amplitude response using PZT is five times greater than that obtained using PVDF.

Time 1μs/ division
Magnitude 50mV/ division

Figure 5 Experimental results using PZT material with ± 15 volts excitation: (a) 5 mm and (b) 10 mm of Carbon Fiber Composite.



Time 1μs/ division
Magnitude 10mV/ division

Figure 6 Experimental results using PVDF material with ± 15 volts excitation: (a) 5 mm and (b) 10 mm of Carbon Fiber Composite.

CONCLUSIONS

The research described in this paper has demonstrated the feasibility of utilizing low voltage excitation for generating ultrasound through carbon fiber composite structures. Ceramic piezoelectric materials such as PZT-5A generate, and therefore detect, ultrasound more readily than PVDF due to a much higher electromechanical coupling factor. However, computer simulation studies has shown that by matching the input and output impedance's of the amplification and excitation circuitry to the PVDF transducer material, substantial improvements in overall sensitivity can be achieved. Further improvements in sensitivity can be achieved by tone burst excitation, however, the correct tone burst frequency must be selected to avoid destructive interference. Therefore, because PVDF has the advantage of being flexible, and arrays can be easily constructed from this material, future work will be directed towards the design and manufacture of pulser/receiver electronics for low voltage excitation of PVDF material.

Successful implementation of low voltage excitation will allow the electronic design to be implemented in an application specific integrated circuit (ASIC). This will significantly reduce hardware size and therefore improve portability. Other advantages are reduced component count therefore increasing reliability and Computer Aided Design and testing capabilities producing fast and accurate prototype systems.

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